FIRS Users' Manual

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1. Introduction to FIRS

The Facility Infrared Spectropolarimeter for the Dunn Solar Telescope is an advanced imaging spectropolarimeter developed by the Institute for Astronomy - University of Hawai'i (P.I. Haosheng Lin) and the National Solar Observatory. This instrument provides simultaneous spectral coverage at visible and infrared wavelengths through the use of a unique dual-armed spectrograph design. The geometry of the spectrograph has been specially designed to capture the Fe I 6302 Å and the FeI 15648 Å or HeI 10830 Å lines with maximum efficiency. In addition, the spectrograph operates in a multiple slit mode. By using narrow band filters, the spectra from four consecutive slit positions can be imaged at once on the same detector. This feature greatly reduces the time necessary to scan across a large area on the sun, making it an ideal instrument for the study of quickly developing active regions.

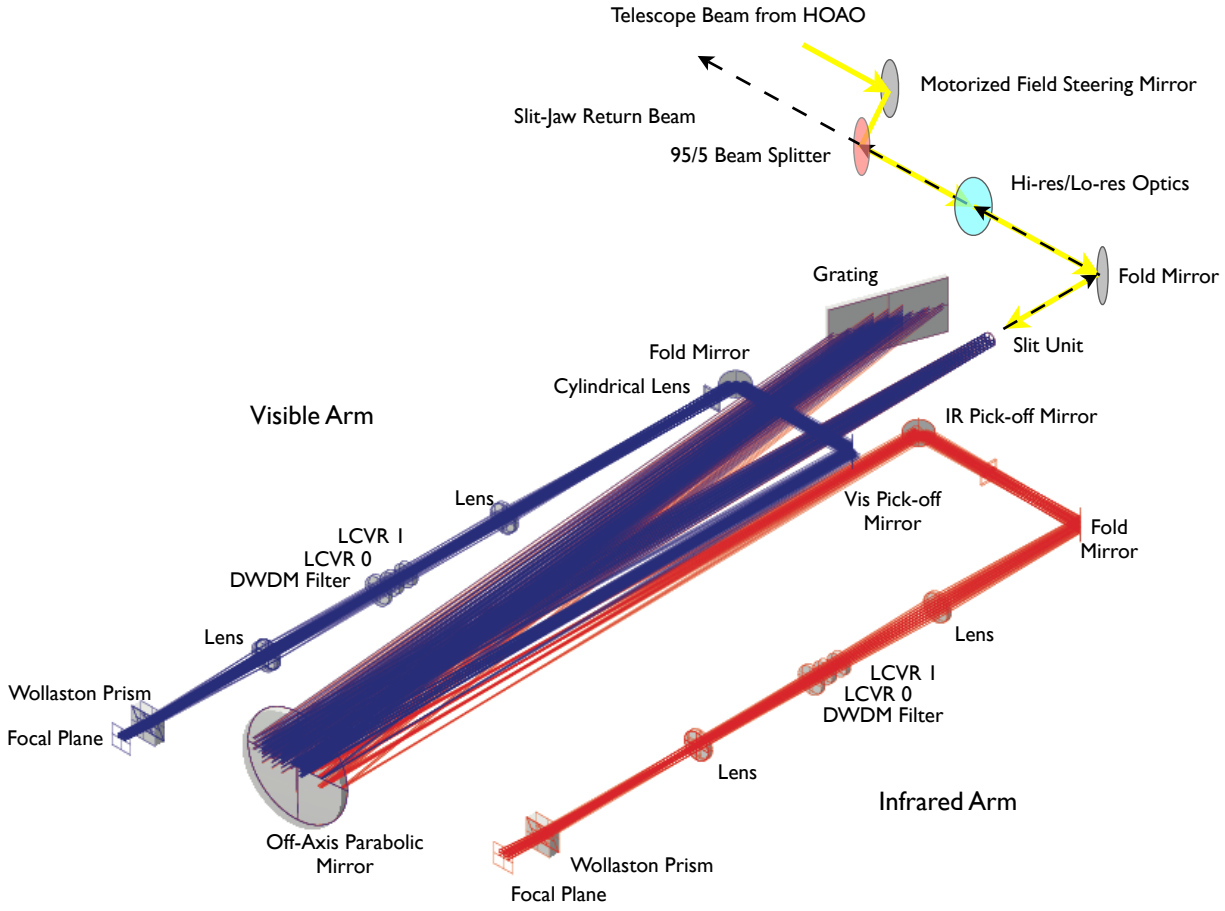


Figure 1. The FIRS optical path.

The current configuration of FIRS with HOAO will deliver diffraction limited observations of the Fe I 6302 Å and Fe I 15648 Å, or the Fe I 6302 Å and He I 10830 Å solar magnetic field diagnostics. Additional beamsplitters placed in the AO optical bench allow FIRS to share the light path with the Interferometric Bidimensional Spectrometer (IBIS), which provides coverage of the chromospheric Ca II 8542 Å line, and the G-band imager without interfering with FIRS observations.

FIRS is an off-axis reflecting Littrow configuration spectrograph which can operate in an f/36 low resolution or f/108 high resolution mode. A diagram of the current optical path is shown in Figure 1. The DST is a 76 cm aperture vacuum tower telescope and provides a beam which has been processed by the High Order Adaptive Optics system (Rimmele et al. 2004). A motorized field scanning mirror and additional optics form an image on the 4-slit unit. Light passes through the slits to an off-axis parabolic mirror which collimates the beam. The beam is then spectrally dispersed by a 31.6 line/mm echelle grating with a 63.5° blaze. For the standard alignment, 6302 Å has been selected from the 90th order, 15648 Å has been selected from the 36th order, and HeI 10830 Å has been selected from the 34th order; the steep blaze angle ensures that there is more light at these widely dispersed, high orders. The dispersed beam is refocused by the parabolic mirror a second time and then travels to the respective pick-off and fold mirrors for the visible and infrared detectors and their optics. Following this point the layout of the essential optics for each arm is identical. Astigmatism is inherent in the spectrograph due to the second reflection from off-axis paraboloid. In order to correct this astigmatism the next focusing element is a cylindrical lens which refocuses the beam along the vertical axis. Following this there are two re-imaging lenses which readjust the size and focus of the image on the camera. Between these two lenses are two liquid crystal variable retarders (LCVRs) which modulate the beam polarization in an efficiency-balanced tuning scheme (and there is space for a linear polarizer and quarter-wave plate for calibration of the LCVRs). Following the polarizers is a DWDM, or dense wavelength-division multiplexing filter, which has been adapted from optical communications technology. This narrow filter has been made especially for each wavelength and ensures that the spectra from adjacent slits do not overlap at the focal plane. A Wollaston prism, or polarizing beam splitter, acts as the analyzer for the modulated beam and vertically separates linearly polarized light into its orthogonal components, and sits immediately before

Table 1. Properties of FIRS

Property	FIRS f/36*	FIRS f/108*
Telescope	76.2 cm Solar Tower	...
Rayleigh limit @ 6302	0.21”	...
Rayleigh limit @ 10830	0.36”	...
Rayleigh limit @ 15648	0.52”	...
Field	174” x 75”	58” x 25”
Vis Spatial Sampling	0.30” x 0.08”/pix	0.10” x 0.03”/pix
IR Spatial Sampling	0.30” x 0.15”/pix	0.10” x 0.05”/pix
Nominal Scan Time**	20 min	...
6302 Spectral Resolution (Sampling)	0.03 (0.01) Å	...
10830 Spectral Resolution(Sampling)	... (0.04) Å	...
15648 Spectral Resolution (Sampling)	0.17 (0.05) Å	...

*Assuming use of a 40 μm slit
**Assuming a 5 sec scan step cadence

the final focal plane. The detector for the infrared side is a Raytheon Virgo 1024 × 1024 HgCdTe array. The detector for the visible side is a Kodak 2048 × 2048 CCD.

A raster of a solar region is produced by stepping the field scanning mirror, moving the image across the slit unit. For a single slit position in the raster both the visible and infrared arms obtain spectral images of each of the four polarization states provided by the LCVRs. The Stokes vector is recreated from these four images in post-processing. This method produces observations of the visible and infrared spectrum which are coincident in space and time with little ambiguity (although differential refraction caused by the Earth's atmosphere can cause a slight shift between the focused telescope image at different wavelengths). Each spectral image consists of eight spectra, where the 4 slits have been vertically separated by the Wollaston prism into their orthogonal polarization states. During a scan the four slits fully sample four adjacent regions and for this reason FIRS shows a significant performance advantage over traditional single slit imaging spectrographs. The properties of the FIRS standard configuration are given in Table 1. The result after post processing is a Stokes data cube for the visible and infrared which contains the Stokes spectrum for each of the consecutive slit positions (for unbinned data, roughly 1000 spatial pixels × 760 scan steps × 400 spectral pixels × 4 Stokes components for the visible wavelength data, and 500 spatial pixels × 760 scan steps × 200 spectral pixels × 4 Stokes components for the infrared wavelength data).

2. Startup Procedure

Make sure the two main power strips are located on the underside of the FIRS main instrument table are on. Following this, the computers (Papaya and Coconut), LCVR controllers, motion controllers, and camera controllers can be turned on. The components in the electronics chassis and the location of power switches is shown in Figure 2.

The cameras should be switched off in the evening, but the computers, LCVR controllers, and motion controller can all be left powered on for the duration of the run. Just be sure to check that the motion controller and LCVR controllers are still working properly the next morning.

2.i. Kodak 2K CCD

Turn the camera on first, the power switch for the CCD is located on the end of the power cable near the camera.

2.ii. Papaya

The computer for the Kodak 2K CCD is a dual boot system running Linux/Fedora and Windows XP. The on/reset button for Papaya is a black square button on the front panel. Linux is the default option upon startup and the operating system under which the camera is run, so nothing needs to be done while the system is booting. At the end of the boot sequence the linux terminal will prompt for the username and password (the end of the boot sequence actually results in rows of text that look like the computer is still booting, I think this is some IDL startup garbage, just press enter and you'll get the login prompt).

login: ******
password: ******

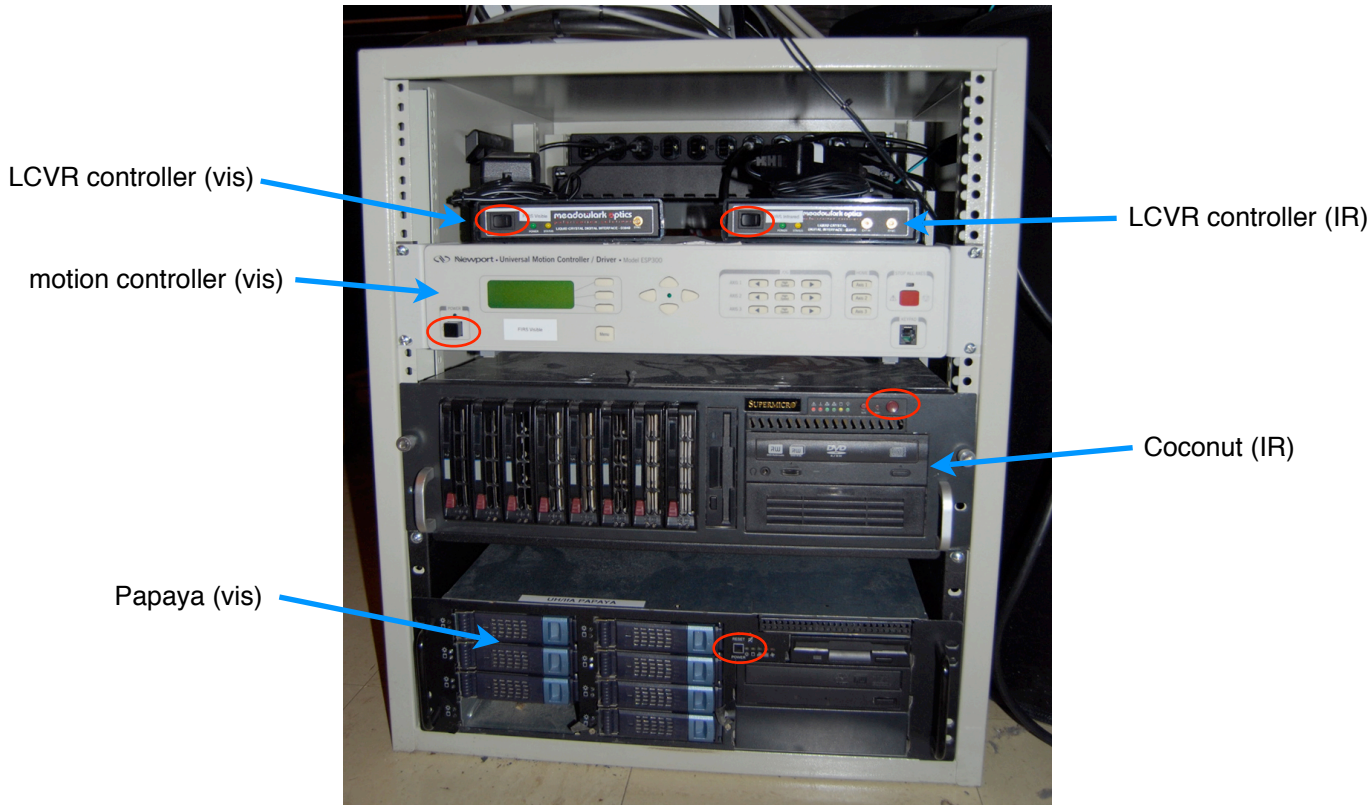


Figure 2. FIRS electronics chassis, the power switches are indicated by the red ovals.

Then at the prompt type:

```
[tic@papaya ~]$ startx
```

and Linux(xwindows) will launch. Papaya has direct control of the Port 4 calibration optics at prime focus. The Java control gui is accessed through the 'port4.jar' icon on the Linux desktop.

Open a terminal window on Papaya. The camera is initialized with the following command:

```
[tic@papaya ~]$ ./start_firs
```

A few lines of output will follow ending with the IDL prompt. Next initialize the camera and start the FIRS visible camera gui:

```
idl> firs
```

The gui will appear and if there is not yet a data folder for the current day it will create one (and tell you that it has, click 'ok'). From the gui take a couple of pictures to make sure the camera is working. Try changing the exposure time and verify that the counts on the camera change accordingly. If the counts do not change you just exit FIRS and IDL and restart from ./start_firs.

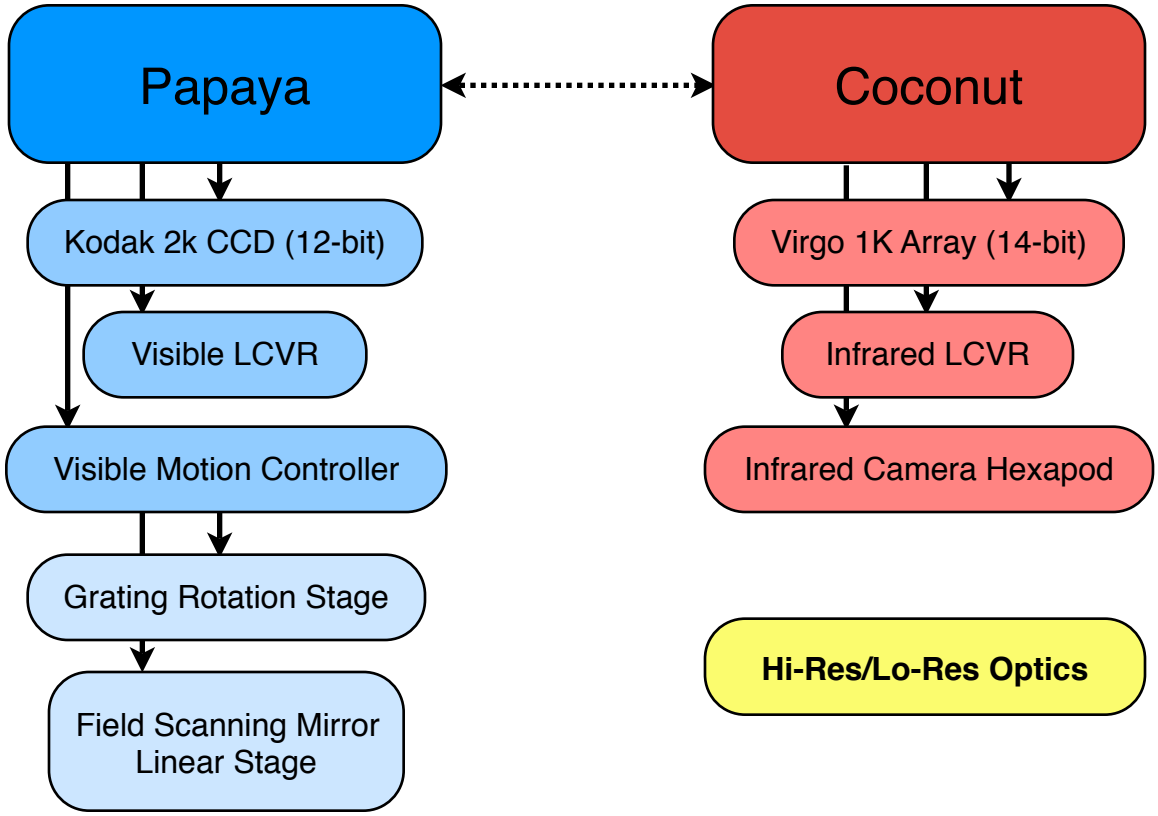


Figure 3. Conceptual map of FIRS electronics hierarchy.

2.iii. Newport Universal Motion Controller/Driver ESP 300

The Newport motion controller attached to the visible-side operates the grating rotation stage and the linear stage for the field scanning mirror. The stages can be moved using the buttons on the motion controller or via the FIRS gui.

Visible Motion Controller:
axis one--rotation stage, spectrograph grating
axis two--linear stage, field scanning mirror

First turn on the power for the motion controller, this is a black button on the far left of the controller. When the controller has completed its startup the display will show three axes and their positions (which will always be zero after startup). The axes will show that they are 'off' on the display. Turn the field scan mirror (axis 2) 'on' by pushing the button immediately to the right of the display. The grating axis can be left off for normal observation modes. Note that only one button can be pushed at a time on the motion controller, and you must wait until a command is finished/an axis has stopped moving before giving another command. The field scanning mirror should be initialized using the 'Home axis' button on the far right of the controller. When the FIRS gui for the visible side is running send the field mirror to its default center scan position by clicking in the "Field Scan Mir" position field and pressing enter. You should also see the image move on the slitjaw camera display.

2.iv. Coconut

The operation of the Virgo 1K infrared array requires a Windows environment. When Windows has finished booting simply enter the login and password. The power button on Coconut is the round dark red button.

If you intend to synchronize the camera operation using the system clock, check the clocks on both computers and make sure that the are close (within 1/4 second). If not, force the computer to check the default internet time server (should be accessible through the task bar clock on both Linux and Windows). File names for the fits data are also produced using the system clock time and it's nice when they match between the visible and infrared data.

2.v. Virgo 1K IR Array

The camera-head electronics and power supply are external to the infrared camera dewar. To startup the camera, the switch on the power supply needs the be switched on and the 12 V adapter for the camera head cooling fan needs to be plugged in. If the cooling fan is left on when the camera is off the array may show "snow" varying of hot pixels on the right side of the image. We think this is due to static buildup on one of the AD cards, so be sure to unplug the fan when the camera is shut down.

On the computer desktop there is a set of three icons at the top of the left-hand screen. First launch the 'Virgo 1K' program (red and yellow hand icon) and turn the camera on in software via the 'On/Off' menu, clicking through the subsequent windows. Launch 'Camera Program' (cyan icons with text 'SEIR'). Leave both of these program windows running in the background or minimized. Start IDL 6.3 using its icon and type 'firs' in the command line to start the FIRS gui.

The Virgo 1K can take images at a maximum of 8 per second, so the minimum exposure time is 125 msec and the exposure time can only be a factor of 125 msec (250, 375, 500, ect.)

2.vi. Meadowlark Optics Liquid Crystal Digital Interface D3040/3050

Flip the switch on the left of the controllers for the visible and infrared LCVRs. A green light will come on and an amber light will blink for a moment and then turn off. The amber light signifies that the controller is communicating with the LCVRs. If the amber light does not blink when the polarimeter is supposed to be running, cycle the power on the controller (no system restart necessary). After the FIRS gui has been started verify that the LCVRs are working properly by taking a test images with the polarimeter on. For the infrared FIRS gui make sure the correct LCVR tuning is being used from the menu Polarimeter>Show LCVR settings. If a sunspot is present on the disk, place on of the slit on the sunspot, verify that polarization signals are present in the polarized Stokes spectra (Stokes Q, U, and V).

2.vii. Infrared Camera Hexapod

The Virgo 1k dewar is enclosed by a fully motorized hexapod mount which is controlled by Coconut via IDL (start a new IDL session and type 'hexapod' in the IDL command line). The hexapod allows the user to specify the X, Y, and Z position and tilt of the array, This position has been carefully determined and should not need to be altered. The hexapod share a power supply with the high resolution beam optics mechanics, be sure not to run both at once.

2.viii. High Resolution Mode Mechanized Optics

The optics for the high and low resolution modes are under the black chimney in front of the slit. In low resolution mode the simply light passes through the 780 mm lens (in the white

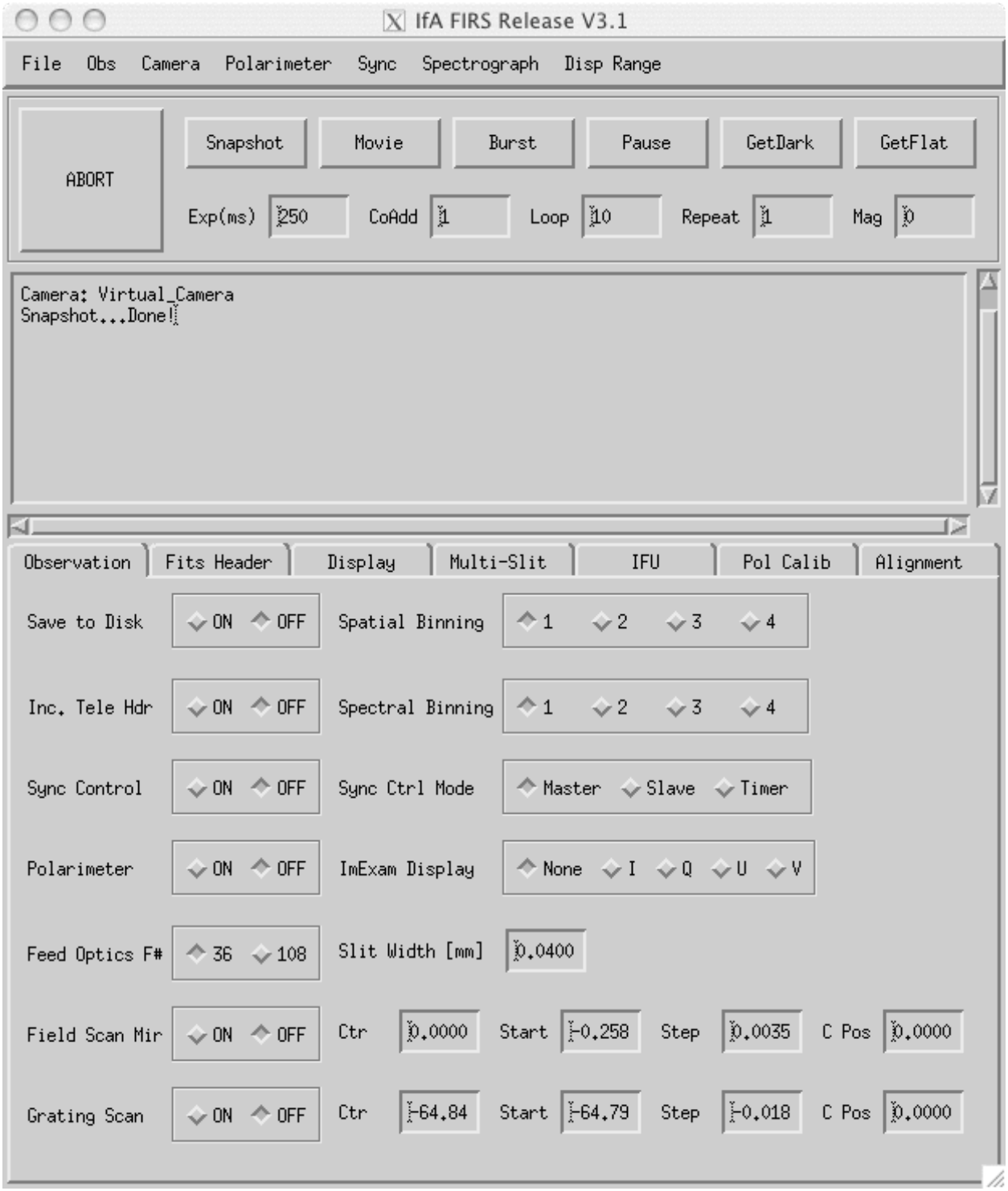

IfA FIRS Release V3.1
File Obs Camera Polarimeter Sync Spectrograph Disp Range
ABORT
Snapshot Movie Burst Pause GetDark GetFlat
Exp(ms) 250 CoAdd 1 Loop 10 Repeat 1 Mag 0
Camera: Virtual_Camera
Snapshot...Done!
Observation Fits Header Display Multi-Slit IFU Pol Calib Alignment
Save to Disk ON OFF
Spatial Binning 1 2 3 4
Inc. Tele Hdr ON OFF
Spectral Binning 1 2 3 4
Sync Control ON OFF
Sync Ctrl Mode Master Slave Timer
Polarimeter ON OFF
ImExam Display None I Q U V
Feed Optics F# 36 108
Slit Width [mm] 0.0400
Field Scan Mir ON OFF
Ctr 0.0000 Start -0.258 Step 0.0035 C Pos 0.0000
Grating Scan ON OFF
Ctr -64.84 Start -64.79 Step -0.018 C Pos 0.0000

Figure 4. The FIRS gui with Observation tab open.

housing) and is folded onto the slit, providing an f/36 beam. In high resolution mode the 780 lens is bypassed and the beam travels to a mirror at the top of the FIRS chimney that provides an f/108 beam at the slit. The optics are mechanized and there is a switch at the slit access port

that puts the chimney fold mirrors in place(on/off switch only for emergencies, leave in the on position). The motor is powered by the same supply as the hexapod, located under the end of the optics table which must be turned on before use.

3. The FIRS Software

3.i. The FIRS Main GUI

The gui, shown in Figure 4, has many menus, buttons, tabs, toggle switches, and input fields. Don't let this fool you into thinking it is complicated. Views of the gui are shown in figures 4-7 and a brief description of all the gui commands is given in the following tables.

Menu	Sub-Menu	Description
File>	Save Current Image	
	Refresh Display	
	Show Data Disk	Shows the current data disk and usage*
	Set Data Disk	
	Show Data Path	
	Set Data Path	
	Debug On	
	Debug Off	
	Exit	
Obs>	Save Obs Parameters	
	Get Obs Parameter File	
Camera>	Show Camera ID	
	NICMOS 3	
	TCM2620	
	Kodak ES1.0	the default Vis camera
	Kodak ES4.0	
	Kodak 2k CameraLink	

Menu	Sub-Menu	Description
	Virtual Camera	
	SEIR IK	the default IR camera
	SEIR 2K	
Polarimeter>	Read/Edit LCVR File	opens a text editor where the LCVR voltage setting can be changed
	Show LCVR Settings	Prints the voltage settings for the LCVRs
	Calibrate LCVR	Runs the LCVR calibration gui
Sync>	Read/Edit Sync File	
	Show Sync Settings	
Spectrograph>		
Disp Range>	...	Preset configurations for the window display ranges for intensity and the QUV components of the Stokes vector

*A note on disk space: The gui shows the amount of disk space in the default directory on startup and will warn you if disk space is running low, however it will not change the data disk for you so this needs to be done manually using the menu: file> data disk.

Button	Description
Abort	Halts whatever imaging process is running after the after the most recent image has been displayed (and saved). Might need to press this a couple of times until the gui responds.
Snapshot	Takes a single frame of data with the specified integration time (one image for intensity or 4 images for full Stokes polarimetry)
Movie	Continuously takes images until 'Abort' is pressed
Burst	Takes the number of images specified by 'Loop', this is repeated the number of time specified by 'Repeat'. This is the primary observation mode and more is described in Section 4: Setting up a Scan.
Pause	Temporarily stops a 'Burst' (or 'Movie') which can then be restarted from the same point in the burst.

Button	Description
GetDark	Takes an image and saves it in temporary memory unless 'Save to Disk' is specified, this dark is used to correct the image displayed by ImExam and is essential for the LCVR calibration.
GetFlat	Takes an image and saves it in temporary memory unless 'Save to Disk' is specified, this image is used to flatfield the image displayed by ImExam.

Fields	Description
Exp(ms)	The exposure length in milliseconds.
CoAdd	The number of exposures to co-add.
Loop	The number of steps in a scan observation, only relevant in burst mode.
Repeat	The number of times to repeat the burst observations.
Mag	The magnification factor of the Imexam image display, 0.0 will scale the image to fit on the screen, 0.5 will show the image rebinned by 1/2, 1.0 will show the image at the proper pixel size.
Message Box	Prints the output messages for processes the program is running.

Toggle	Sub-Toggle/ Field	Description
Observation Tab		
Save to Disk		Saves all of the data taken to a file labeled with the date and time in the format yyyymmdd.hhmmss.number. For a movie or snapshot the number ending is '0000', however for burst mode all of the images in the burst are labeled with the starting time of the burst and the number in the loop.
Spatial/Spectral Binning		Rebins the data in the spectral or spatial dimension by the specified factor before saving.
Inc. Tele Hdr		Includes the telescope parameters and pointing information in the fits image header.

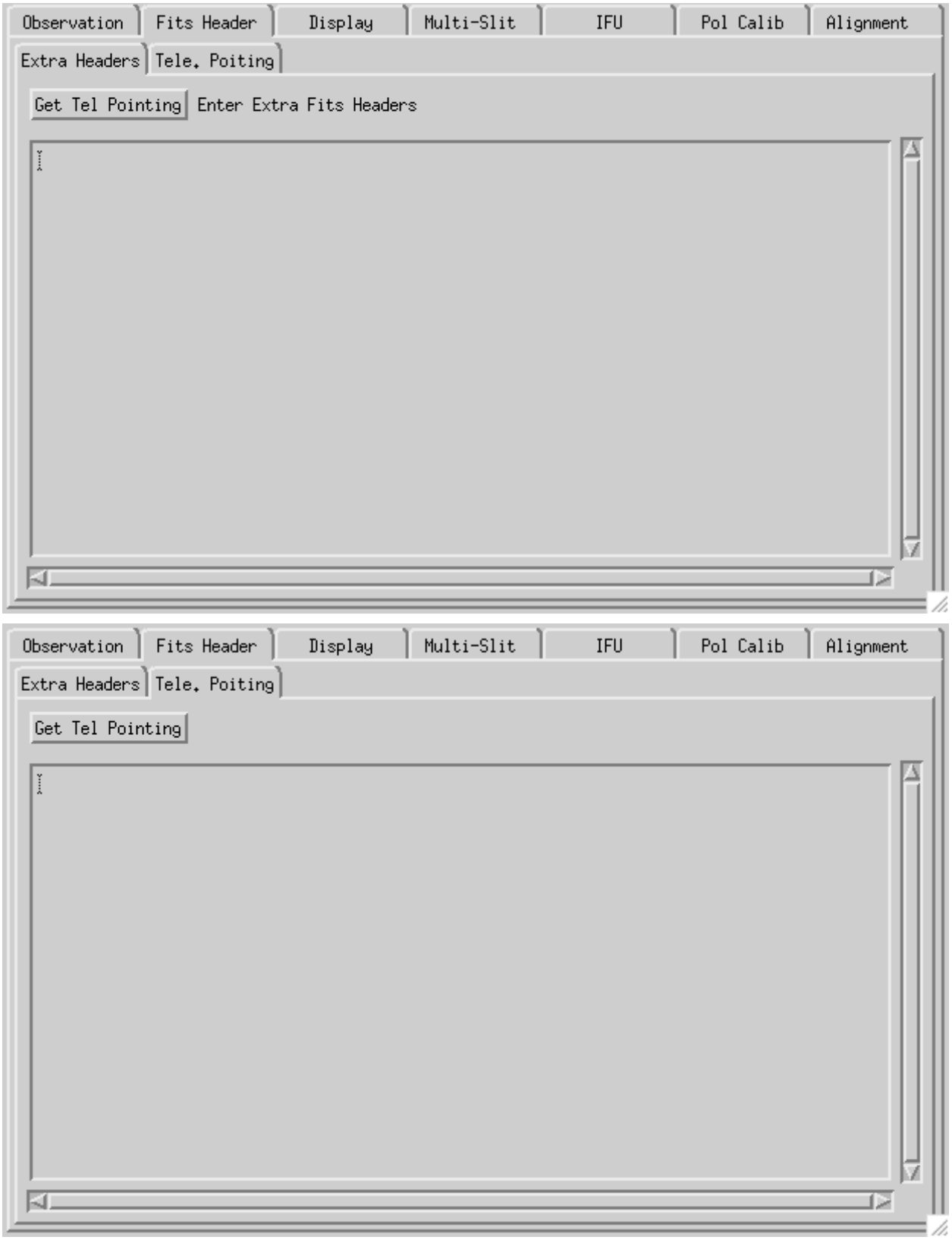


Figure 5. The Fits Header tabs.

Toggle	Sub-Toggle/ Field	Description
Sync Control		Synchronizes operation of the visible and IR cameras using a network handshake or timing file.
	Sync Control Mode	'Master' and 'Slave' are for the network handshake syncing. The 'Master' is the visible side which talks to the motion controller and the 'Slave' is the IR side. 'Timer' uses the system clocks and a timing file to take a synchronized scan.
Polarimeter		Turns the LCVRs on and takes full Stokes vector data, 4 frames.
	ImExam Display	Selects which of the stokes vector components to display in ImExam
Feed Optics F#		Indicates which feed optics are currently in use (but does not actually change them).
Slit Width		Input field for the width of the slit in the selected unit
Field Scan Mir		The field scanning mirror will step the distance input in the 'Step' field for each observation when in Burst mode.
	Ctr, Start, Step, C Pos	These fields define positions in millimeters for 'Field Scan Mir'. Clicking in any of these boxes and pressing enter will send the field scanning mirror to the position value specified. 'Center' is the center of the scan. 'Start' defines the start position of a scan, and 'Step' defines the distance between scan positions. 'C Pos' is the position that the stage will return to when the scan is complete.
Grating Scan		The grating will step the distance(in degrees) specified by the parameters in the adjacent fields when in burst mode.

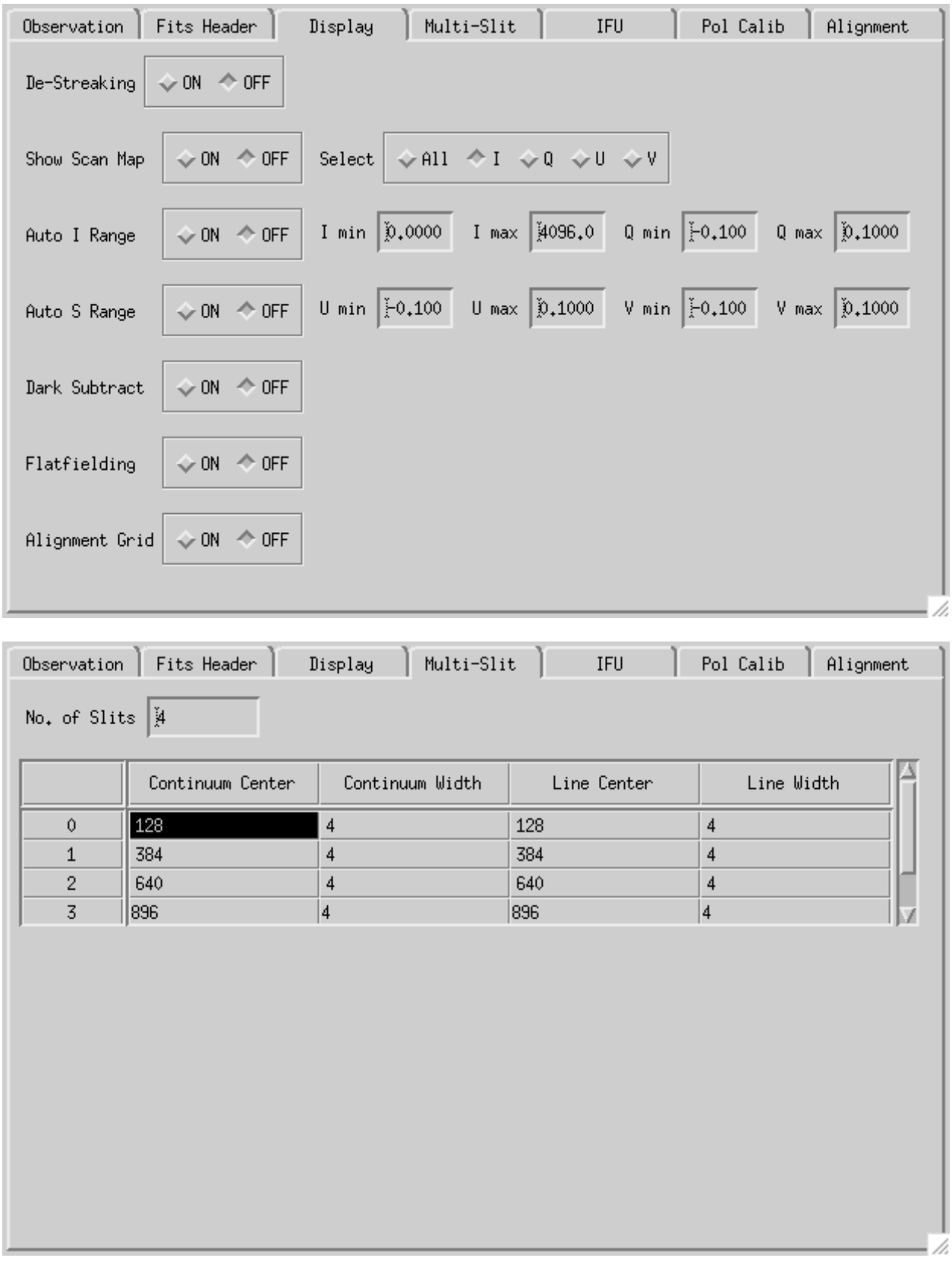
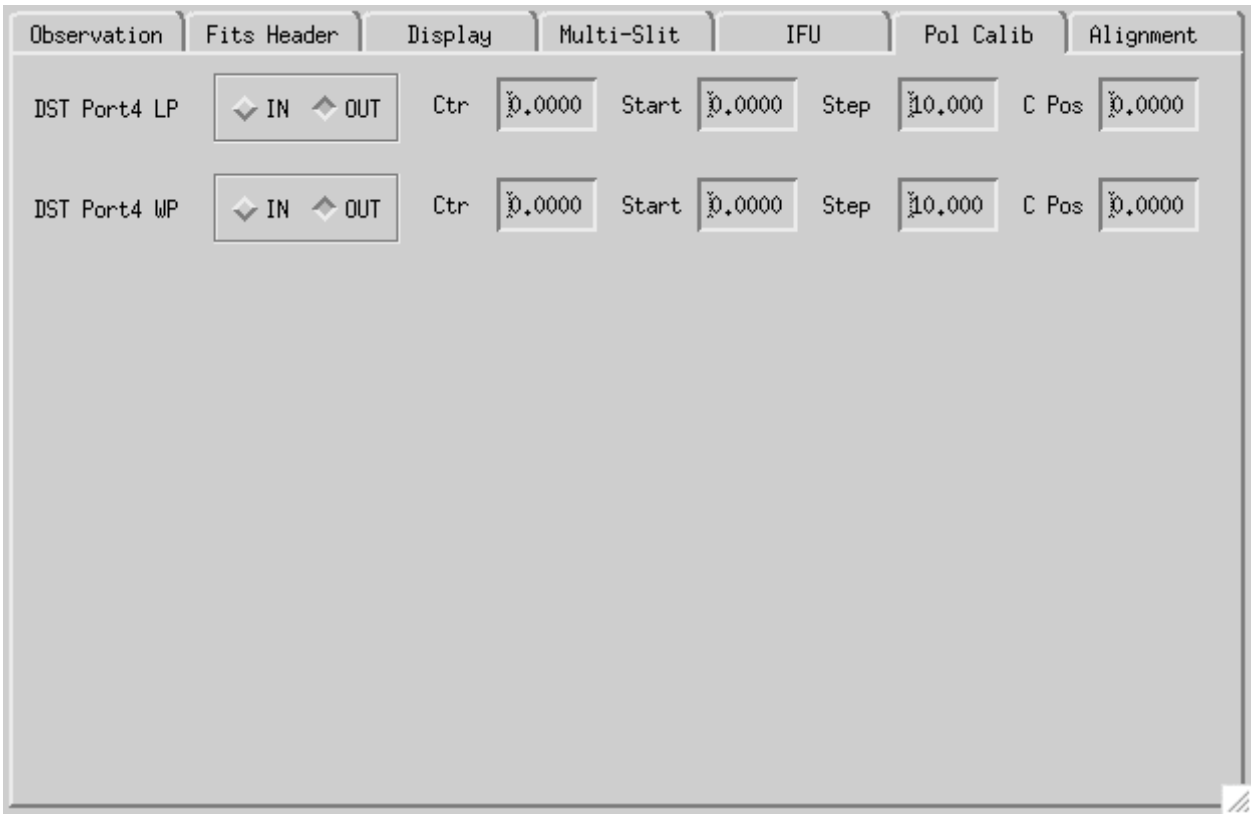


Figure 6. The Display and Multi-Slit tabs.

Toggle	Sub-Toggle/ Field	Description
	Ctr Start, Step, C Pos	These fields define positions in degrees for 'Grating Scan.' Clicking in any of these boxes and pressing enter will send the grating to the position value specified. 'Center' is the center of the scan, and where the spectrum is centered on the detector. 'Start' defines the start position of a scan, and 'Step' defines the distance between scan positions(for the grating this is in degrees per unit slit step). 'C Pos' is the position that the rotation stage will return to when the scan is complete.
Fits Header Tab		
Extra Headers		Additional comments about the observation that you would like to be written into the fits header go here.
Tele. Pointing		The telescope pointing information appears in this field when you click the "Get Tel Pointing" button.
Display Tab		
De-Streaking		Set this toggle to remove streaking from the Q, U, and V components of the Stokes vector.
Show Scan Map		Builds a scan map based on information given in the 'Multi-Slit' tab.
	Select	Selects the spectrum to build the map from.
Auto I Range		Automatically sets the display range of the intensity component of the stokes vector in the ImExam data display.
Auto S Range		Automatically sets the display range of the polarized components of the stokes vector in the ImExam data display.
	I, Q, U, V min and max	Sets the image display range for the Stokes Display.
Dark Subtract		Applies the most recent dark to the image displayed by ImExam, is is not applied to the data written to disk (?).



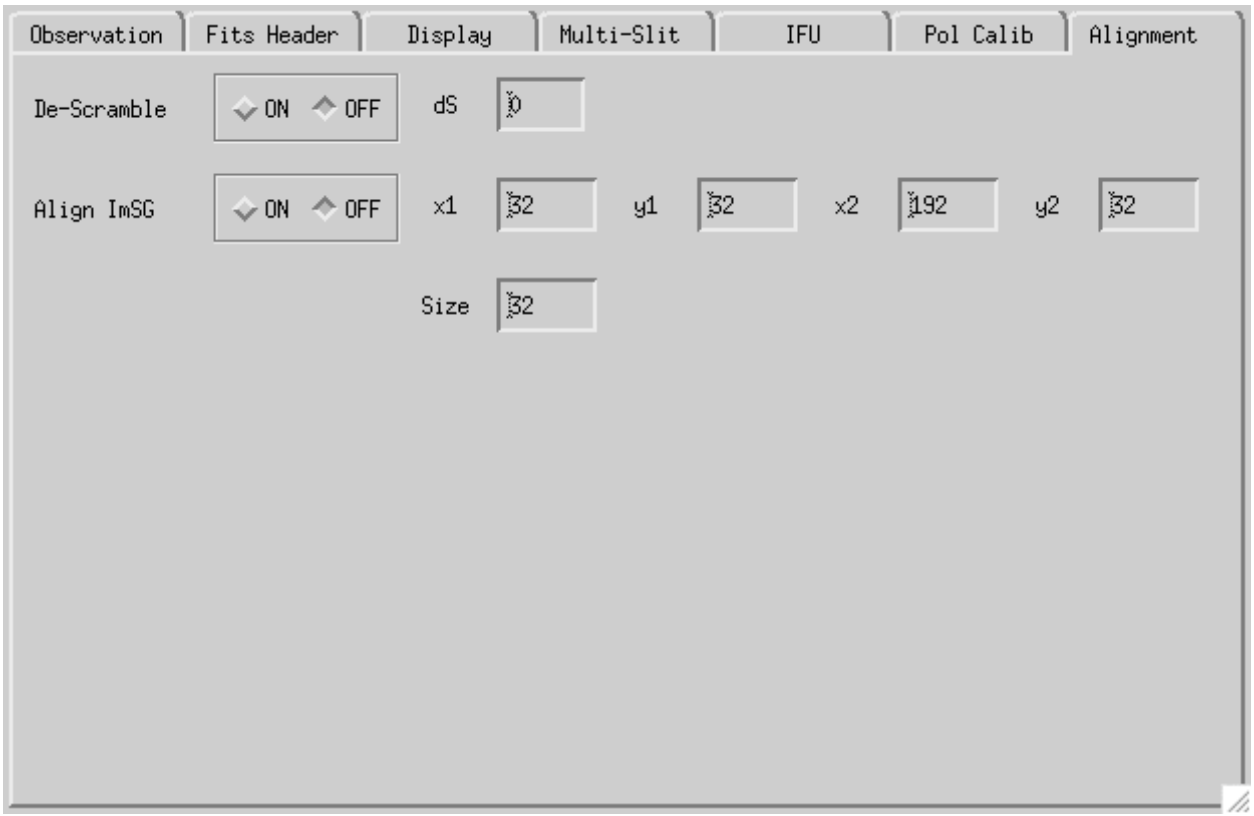
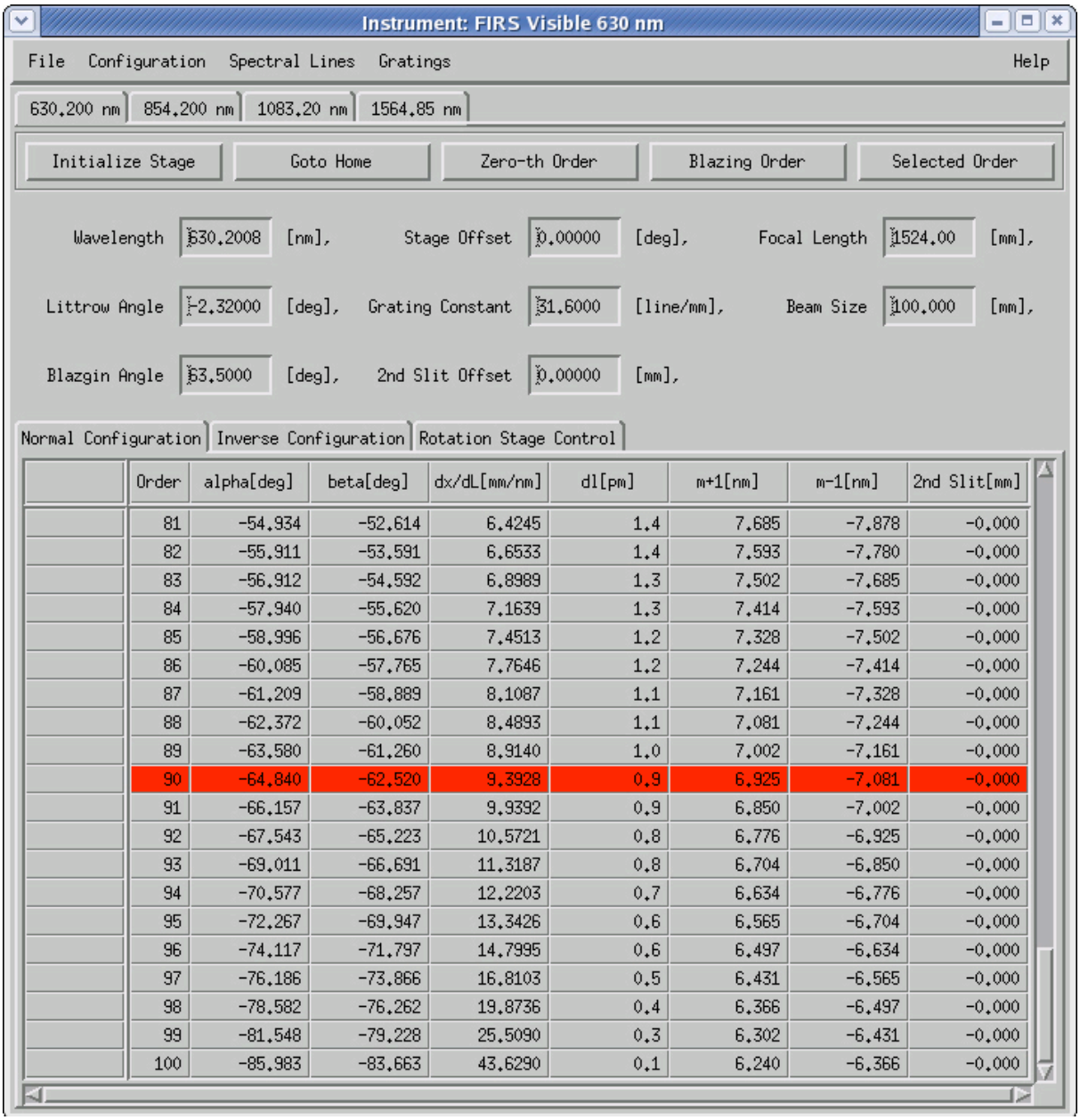


Figure 7. The Pol Calib and Alignment tabs.

Toggle	Sub-Toggle/ Field	Description
Flat Fielding		This applies the most recent flat field to the image displayed in the ImExam window, it is not applied to the data written to disk (?)
Alignment Grid		Overlays a grid on the displayed image for alignment of the instrument.
Multi-Slit Tab		
No. of Slits		The number of slits in the slit unit, usually 4.
Continuum Center		The pixel index for the center of a continuum window.
Continuum Width		The width of the continuum window in pixels.
Line Center		Position of the main line of interest, in pixels.
Line Width		Width of the line, in pixels.
IFU		
		nothing here for now
Pol Calib		
DST Port4 LP		Places the port 4 prime focus LP in the beam for the polarimetry calibration of FIRS.
DST Port4 WP		Places the port 4 prime focus WP in the beam for calibration of FIRS
	Ctr, Start, Step, C Pos	These fields define positions in degrees for the LP or WP. Clicking in any of these boxes and pressing enter will send the WP to the position value specified. 'Center' is the position for the center of the burst. 'Start' defines the start position of a scan, and 'Step' defines the distance between positions. 'C Pos' is the position that the rotation stage will return to when the burst is complete.
Alignment		
De-Scramble		

Toggle	Sub-Toggle/ Field	Description
	dS	
Align ImSG		
	x1, y1, x2, y2, size	

*'Stokes Display' and 'Remove Streaking' take a little extra processor time, leave them off if it's necessary to run a little faster, but in general it is good to see the Stokes data so you can be sure things are working.



	Order	alpha[deg]	beta[deg]	dx/dL[mm/nm]	dl[pm]	m+1[nm]	m-1[nm]	2nd Slit[mm]
	81	-54.934	-52.614	6.4245	1.4	7.685	-7.878	-0.000
	82	-55.911	-53.591	6.6533	1.4	7.593	-7.780	-0.000
	83	-56.912	-54.592	6.8989	1.3	7.502	-7.685	-0.000
	84	-57.940	-55.620	7.1639	1.3	7.414	-7.593	-0.000
	85	-58.996	-56.676	7.4513	1.2	7.328	-7.502	-0.000
	86	-60.085	-57.765	7.7646	1.2	7.244	-7.414	-0.000
	87	-61.209	-58.889	8.1087	1.1	7.161	-7.328	-0.000
	88	-62.372	-60.052	8.4893	1.1	7.081	-7.244	-0.000
	89	-63.580	-61.260	8.9140	1.0	7.002	-7.161	-0.000
	90	-64.840	-62.520	9.3928	0.9	6.925	-7.081	-0.000
	91	-66.157	-63.837	9.9392	0.9	6.850	-7.002	-0.000
	92	-67.543	-65.223	10.5721	0.8	6.776	-6.925	-0.000
	93	-69.011	-66.691	11.3187	0.8	6.704	-6.850	-0.000
	94	-70.577	-68.257	12.2203	0.7	6.634	-6.776	-0.000
	95	-72.267	-69.947	13.3426	0.6	6.565	-6.704	-0.000
	96	-74.117	-71.797	14.7995	0.6	6.497	-6.634	-0.000
	97	-76.186	-73.866	16.8103	0.5	6.431	-6.565	-0.000
	98	-78.582	-76.262	19.8736	0.4	6.366	-6.497	-0.000
	99	-81.548	-79.228	25.5090	0.3	6.302	-6.431	-0.000
	100	-85.983	-83.663	43.6290	0.1	6.240	-6.366	-0.000

Figure 8. Spectrograph GUI.

3.ii. The Spectrograph GUI

If it is necessary to change the angle the spectrograph grating, the spectrograph GUI can be opened by selecting the desired wavelength from the 'Spectrograph' menu or by typing the command 'spectrograph' in the IDL command line. This opens a window like the one shown in figure 8. If the spectrograph parameters are altered push the 'ReCalculate' button, select the desired order and push the 'Goto Selected Order' to move the grating to the new position.

The correct values for default 6302/15648 Å setup are:

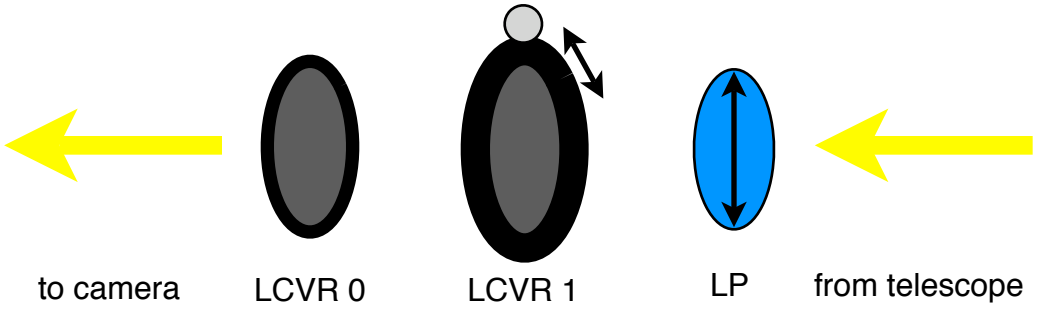
grating constant: 31.6 mm^{-1}
spectrograph angle: -3.75°
wavelength: 15648 Å
grating offset: 0.0°

select 36th order, this configuration gives the 90th order of 6302 on the CCD.

3.iii. The LCVR Calibration GUI

With time and temperature changes the retardance of the LCVRs will drift. When the drift becomes significant it is time to recalibrate the LCVRs. Calibration is done separately for the visible and infrared. The configuration for calibration should be similar to that for solar flat-fields: sun center with the telescope out of focus.

For the LCVR pair of your choice, first take a dark with the exposure length you intend to use for the calibration using the 'GetDark' button. Open the LCVR calibration gui from the 'Polarimeter' menu. Place the linear polarizer in the beam and set the angle to 0°. There are two LCVRs and we calibrate each separately. If it seems necessary, the LCVR which is not being calibrated may be removed from the beam as there is sometimes significant retardance at zero voltage. LCVR 0 is closest to the camera and LCVR 1 is furthest from the camera (or first in the beam). To begin the calibration of LCVR 0 select it in the LCVR toggle box and set the region of the array you wish to use by entering the values into the x1, x2, y1, and y2 boxes (we use the full extent of the bottom beam something like 0:1023, 0:500 for the IR and 0:2047, 0:1000 for the visible). The default V0=0.0, V1=10.0, and dV=0.25 are probably fine for a first coarse calibration but change dV to 0.125 once you are confident you are going to get a good calibration. Turn on Imexam if you want and hit the 'Calibrate' button. The LCVR controller is cycling through voltages and you can see the result as rapid increase in intensity and a gradual drop to zero (if you see the reverse you have chosen your beams backwards). When the calibration is done the intensity vs. voltage curve and its best fit will be plotted in the main window



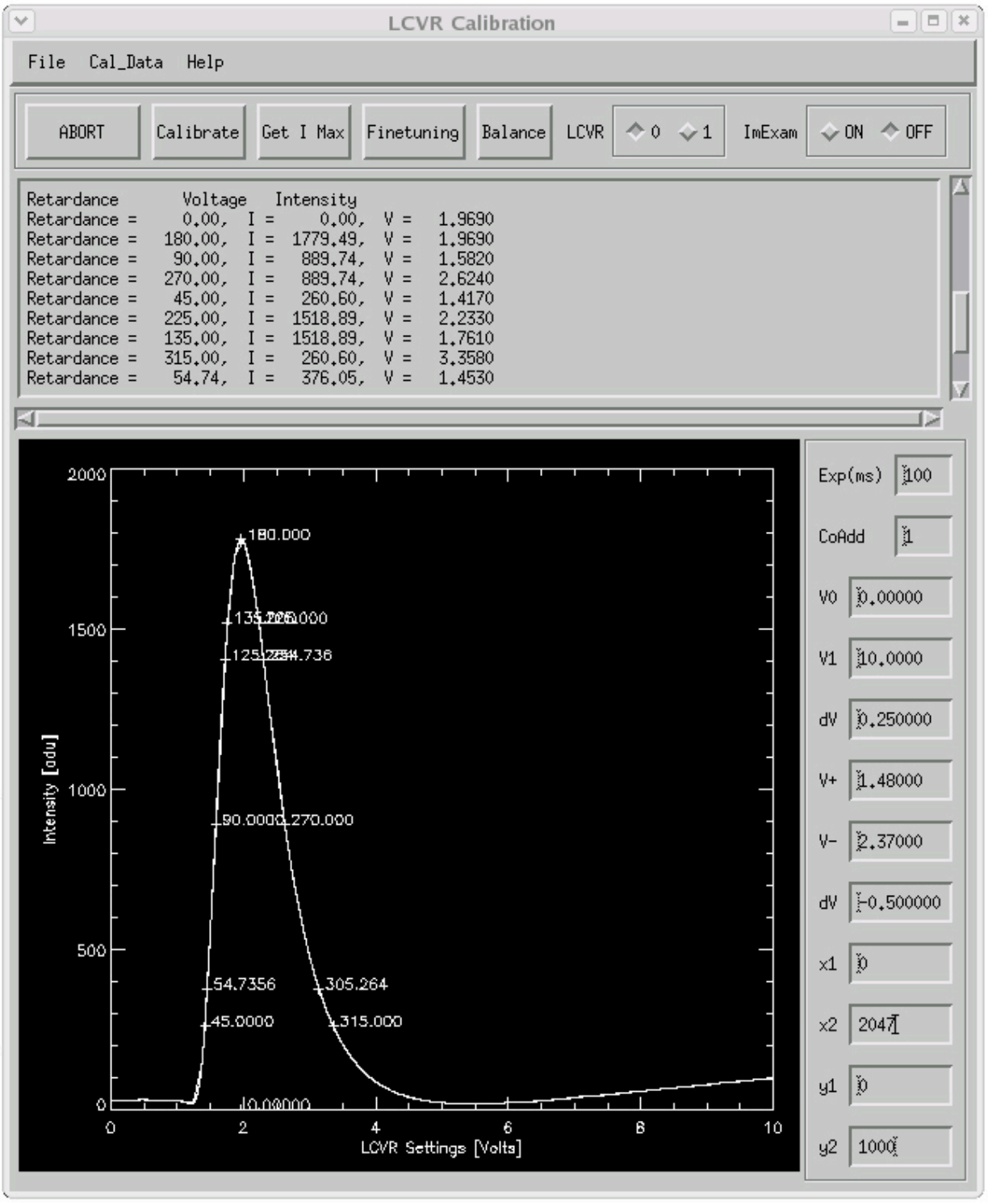


Figure 9. LCVR Calibration GUI.

and the voltage values for the necessary retardances will be marked by crosses on the plot. For a good curve all the crosses except 0° will fall on the line. A reasonable looking calibration will look like the gui shown in figure 9.

LCVR 1 needs to be rotated by 45° just during its calibration, move the knob on the LCVR to the top and when you are finished with the calibration be sure to move it back down to the side. Change the LCVR toggle to '1' in the gui and run the calibration as above.

After the calibration the voltage values that have been determined for the retardance need to be entered into the tuning file. From the FIRS gui select 'Read/Edit LCVR File' from the Polarimeter menu. In the default directory select 'lcvr.tune.default' and use the text editor to enter the values that were printed in the output text box in the LCVR calibration gui, if you lose these values you can reload the file from the 'Cal_Data' menu, these are stored separately for LCVR 0 and 1, bust pick the most recent. 'lcvr.tune.default' should say which values are need, enter the voltages, save, and exit. For the new tuning file to take effect 'Read/Edit LCVR' file again and exit without making any changes.

Be sure to test the new setup using the FIRS calibration linear polarizer and 1/4 waveplate just in front of the LCVRs. The cross-talk between input Q, U, and V states should be at the 10% level or below. We are working on a fine tuning procedure to make this calibration even better.

4. Using the Instrument

The imaging components of the FIRS spectrograph are separate and are controlled independently by each computer, however the mechanical components are not. The visible arm computer(Papaya) controls the motion controller for the grating and slit unit so while the visible side of the spectrograph can be run separately, the infrared side must be run in tandem with the visible side. We'll focus first on taking images and setting up a scan using the visible side, then we'll consider how to use the full system.

4.i. Taking an Image

Set 'Exp' and 'CoAdd'
- Turn on 'Save to Disk' if you wish to save the image
- Type in the 'Fits Header' if you are saving the image

Move the field scanning mirror to the desired position by typing in one of the position boxes and pressing enter
Turn on 'Polarimeter' if you want a full Stokes image
Press the 'Snapshot' button

4.ii. Taking a Movie

This is the same as taking a single image, but images are taken continuously at a single slit position, so we recommend leaving 'Save to Disk' off.

Set 'Exp' and 'CoAdd'
- Turn on 'Save to Disk' if you wish to save the images
- Type in the 'Fits Header' if you are saving images

Move the field scanning mirror to the desired position by typing in one of the position boxes and pressing enter
Turn on the 'Polarimeter' if you want a full Stokes image
Press the 'Movie' button
Press the 'Abort' button to stop the movie

4.iii. **Taking a Single Wavelength Scan** (visible)

Set 'Exp', 'CoAdd'
Turn on 'Save to Disk'
Set slit scan 'Step'
Set 'Loop'
Turn on 'Slit Scan'
    Set slit scan 'Ctr'
    Set 'Start' position for the slit scan
    Set 'Step'
Turn on 'Polarimeter' for full Stokes data
Type 'Fits Header' and 'get telescope pointing'
Press the 'Burst' button to start the scan

FIRS has a variety of slits to pick from, they are listed in Table 2. The size of the scan step and number of steps in a scan can be adjusted arbitrarily, however to achieve optimal sampling we have set the step size equal to the slit width. For a fully sampled field using the 30 or 40 μm slit the parameters should be set as follows:

scan step = 0.030, 0.040 μm
loop = 190, 145
scan center = 12, 12 mm
start = 9.15, 9.12 mm

Table 2. Available Slit Units

Slit Name	Number of Slits	Slit Width (μm)	Slit Length (mm)	Slit Spacing (mm)
15 μm short	4	15	10.0	5.70
15 μm long	4	15	20.48	5.70
30 μm short	4	30	10.0	5.70
30 μm long	4	30	20.48	5.70
30 μm double	2	30	20.48	11.4
40 μm single	1	40	20.48	---
40 μm long	4	40	20.48	5.80

4.iv. **Taking a Tandem Wavelength Scan** (dual visible and infrared)

There are two modes which allow the visible and infrared camera systems to take observations as a coordinated scan. For 'Timer' mode both computers wait for a specific time to start an observation. A timing file set from the 'Sync' menu contains the seconds at which new observations are begun and when an observation finishes it waits until the next second specified in the timing file. For 5 second timing observations are started at the beginning of the next

Table 3. Scan Step Optimization

Slit	Number of Scan Steps
4 slit, 15 μm	380
4 slit, 30 μm	190
2 slit, 30 μm	380
1 slit, 40 μm	---
4 slit, 40 μm	145

minute after 'Burst' is pushed and are taken at 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 55 seconds for each minute until the end of the burst. Both computers are effectively running separately so it is important to set the exposure and co-add such that the observations for the visible and infrared side take about the same amount of time (this may seem easy but in practice it takes a couple of tests to get the right timing down, the exposure and co-add will of course be different for the visible and infrared cameras). This is also why the system time for each computer must be set accurately.

For 'Master' and 'Slave' mode the computers are coordinated through a network connection and when an observation finishes on one computer it will wait for the other computer to finish its observation before starting the next one. No special timing is necessary and the exposure length and co-add can be set as desired. This mode is preferable and runs faster than 'Timer' mode. The 'Master' is the visible-side computer which controls the field scanning mirror and the 'Slave' is the infrared-side computer.

For the (Master) visible side:
- Set 'Exp', 'CoAdd', and 'Loop'
- Turn on 'Save to Disk'
- Set 'Spatial/Spectral Binning' factor
- Turn on 'Sync Control', set 'Master'

or
- set 'Timer' and load a timing file via the 'Sync' menu
- Turn on 'Field Scan Mir'
  - Set the 'Ctr', 'Start', and 'Step'
- Turn on 'Polarimeter'
- Turn on 'Inc. Tele Hdr'
- Type 'Fits Header' comments
- Press the 'Burst' button to start the scan

For the (Slave) infrared side:
- set 'Exp', 'CoAdd', and 'Loop'
- turn on 'Save to Disk'
- Turn on 'Sync Control', set 'Slave'

or
- set 'Timer' and load a timing file via the 'Sync' menu

turn on 'Polarimeter'
type 'Fits Header' comments
press the 'Burst' button to start the scan

Repeating a Scan:

The 'Repeat' field makes it possible to repeat a scan many times over a long period. This is only recommended when the seeing is fair and stable. When the seeing conditions are more erratic it is important leave time between scans to get a new AO flat field so that the image resolution is optimal during observations.

4.v. Switching Wavelengths

The infrared arm of FIRS can swap between He I 1083 and Fe I 1565 nm modes by changing a few optics and software settings. Switch off the power to the IR LCVR controller. On the IR side of the FIRS optical bench add/remove:

For Fe I 1565 nm:
1565 nm DWDM filter
1565 nm blocking filter
1565 nm LCVRs (and swap cables)

For He I 1083 nm:
1083 nm DWDM
1083 nm LCVRs (and swap cables)

Move the final lens before the camera to the position indicated in the bench using the digital micrometers. Finally, in the FIRS IR gui change the LCVR tuning file, selecting in the menu Polarimeter> Read/Edit LCVR File. Select the proper lcvr.tune.default file for the wavelength. Then turn the LCVR controller back on and verify that it is working.

4.vi. Switching Spatial Resolution

To switch from low to high resolution optics (or vice versa), make sure the power supply for the F/108 mirror tower is turned on. Switch the power on the F/108 mirror tower controller to 'ON'. In the FIRS gui set the "high res/low res" toggle switch on the F/108 mirror tower controller to select the resolution mode. Note: The field scan mirror scan step and scan starting position will be scaled automatically by the software.

4.vii. Calibration Procedures

Flat Fields

Solar flats are produced from a full Stokes spectra taken at disk center with the AO mirror un-flat and random guiding. Flats should be taken every couple of scans and before swapping between 1083 and 1565 nm. The slits should be as evenly illuminated as possible, with the scanning mirror at the center the field. Exposure time and co-add for the solar flat should be the same as the data.

For either a solar or lamp flat:
set 'Exp' and 'CoAdd'

set 'Loop', (16)
set the 'Field Scan Mir' to the center
turn on 'Save to Disk'
turn 'Polarimeter' on
type 'Fits Header' comments
push the 'Burst' button to start the sequence of flat fields

Note: Lamp flats can be taken with the flat field lamp located under the FIRS optical table. The lamp is connected by a large core fiber optic to a collimator and a set of fold mirrors places the light on the slit. The last fold mirror must be slid into place (otherwise it would block the solar beam) and there are three kinematic pushers on the table for its positioning. If the lamp is on and the final mirror is not in place the whole AO bench is illuminated so be careful if calibrations are being done for another instrument. The lamp is about half as bright as the sun in the IR and about 1/4 times as bright for the visible, so chose an integration time 2-4 times that for the data. The lamp has an uneven illumination pattern so I have not found it very useful for flat-fielding the data.

Darks

With the dark slide in place take a burst at the default slit position with the exposure length of the data and flat field scans.

set 'Exp' and 'CoAdd', same as for the data, flat field, and calibration images
set 'Loop', (16)
turn 'Save to Disk' on
'Polarimeter' off
type 'Fits Header' comments
push the 'Burst' button to start the sequence of darks

Polarimetry Calibration

The LCVRs change with operation time and temperature so it is important to obtain a new calibration every few hours during observations. A well sampled polarization curve with 10° sampling will lead to a more accurate polarization calibration. The motorized optics at the DST Port 4 prime focus are available for this purpose. There are also calibration optics which can be put in place immediately before the LCVRs in each arm of FIRS and must be adjusted by hand, although these calibration optics may become motorized in the future.

When using either set of calibration optics the procedure will be:
set the LP (linear polarizer) to 0°
cycle the WP (1/4 wave plate) through 360° using 10° increments or better
take full Stokes observations at each position

Papaya has direct control of the Port 4 calibration optics at prime focus. The Java control gui is accessed through the 'port4.jar' icon on the Linux desktop. The polarization calibration data can also be set up to run automatically using the FIRS gui. The 'Pol Claib' tab is used to set up a calibration burst:

put the 'DST Port 4 LP' in with 'Ctr'=0, 'Start'=0, and 'Step'=0
put the 'DST Port 4 WP' in with 'Ctr'=180, 'Start'=0, and 'Step'=10
turn on 'Save to Disk'
set 'Binning' same as for the data
turn on 'Inc. Tele Hdr'
type 'Fits Header' comments
turn on 'Polarimeter'
push 'Burst'

Note about FIRS polarizers: The infrared side linear polarizer is off by about 10°, ie 10° on the scale = 0° actually

5. Troubleshooting

IDL

If IDL becomes unresponsive try entering the command 'retall' in the IDL command line a few times. If it does not recover after this restart it in the same way as for the startup procedure.

Imexam

If Imexam becomes frozen, close any offending windows and type '`retall`' in IDL command line and redisplay the last image by typing '`imexam, image`'.

LCVR Controllers

The amber light signifies that the controller is communicating with the LCVRs. If the amber light does not blink when the polarimeter is supposed to be running, cycle the power on the controller (no other hardware or software restart is necessary).

LCVR tuning

If the stokes vector for the IR does not look right (check against example data) and the LCVR controller is working, you may be using the wrong tuning file. Try swapping it from the menu using Polarimeter>Read/Edit LCVR File

Newport Motion Controller

Sometimes the communications between Papaya and the motion controller hang. Turn off the motion controller power and try typing 'retall' in the terminal running IDL (if this doesn't work exit IDL restart the FIRS software from ./start_firs). Power on an initialize the motion controller and try again.

If a controller error occurs during operation(limit switch ect.) the controller will emit a loud beep and an 'E' will appear in the upper left corner of the display. This error needs to be cleared before the controller can be used again, either by navigating the menu or cycling the power on the controller.

Virgo 1K Array

If the cooling fan is left on when the camera is off the array may show "snow" varying of hot pixels on the right side of the image in I, and looks even worse for Q, U, and V. We think

this is due to static buildup on one of the AD cards.

6. Observing and Calibration Short Lists

After reading everything in the preceding sections you should have a very good handle on how the spectrograph operates. The short lists that follow summarize the procedures for startup, shutdown, and operation.

Startup for FIRS Visible

Turn the power on for:
- Kodak 2K camera
- visible computer, Papaya
- visible LCVR controller

Following computer startup:
- use the login and password
- type 'startx' at the prompt

Start FIRS

open a terminal and type:

```
./start_firs
idl> firs
```

Turn the power on for:
- Newport motion controller

Initialize the motion controller:
- turn axis 2 'on' (field scanning mirror)
- 'home' axis 2

In the FIRS visible gui verify:
- communication with field scanning mirror
- communication with LCVR
- camera exposure times

Short Startup for FIRS Infrared

Turn the power on for:
- IR computer, Coconut
- IR LCVR controller
- Virgo 1K camera power supply
- plug in Virgo camera-head fan power

Following computer startup:
- use the login and password

Start FIRS

FIRS program icons are at the top of the screen:

start 'Virgo 1k', turn the camera on via the menu and click through the boxes

start 'Camera 2.9'

start 'IDL' then 'idl> firs'

In the FIRS infrared gui verify communication with:
- LCVR

Short Shutdown for FIRS Visible

Exit the FIRS gui, close all windows, shutdown Papaya
Turn everything off

Short Shutdown for FIRS Infrared

Exit the FIRS gui
in 'SEIR Camera' click the exit button
in 'CamIRa - Virgo 1k x 1k' program turn camera off using 'On/Off > Off' in the menu
exit using the menu 'File > Exit'
turn off camera head power
unplug 12V adapter for camera head fan!!

Observations

set 'Exp'
set 'Co-Add'
set 'Loop'(number of steps in scan)
'Save to Disk' on
'Inc. Tele Hdr.' on
'Sync Control' on for a tandem scan and 'Master' or 'Slave' set appropriately
'Polarimeter' on
'Feed Optics' set correctly for f/36 or f/108
'Field Scan Mir' on, check positions
write 'Fits Header' comments

push 'Burst'

Parameters for Full-Field Scan, F/36 Mode, ~ 10 sec/step (25 min) **DEFAULT**

Camera	Fe I 630 nm	Fe I 1565 nm	He I 10830
Exposure Time (msec)	350	125	250
CoAdd	2	3	2
Loop	145	145	145
Repeat	1	1	1

Deep Integration, F/36 Mode, ~16 sec/step (10 min)

Camera	Fe I 630 nm	Fe I 1565 nm	He I 10830
Exposure Time (msec)	350	125	250
CoAdd	6	8	2
Loop	32	32	32

Camera	Fe I 630 nm	Fe I 1565 nm	He I 10830
Repeat	1	1	1

Deep Integration F/108 Mode ~30 sec/step (16 min)

Camera	Fe I 630 nm	Fe I 1565 nm	He I 10830
Exposure Time (msec)	500	500	500
CoAdd	6	8	8
Loop	32	32	32
Repeat	1	1	1

Polarimeter Calibration

With the same parameters as the data
Disk center, AO mirror un-flat
In the 'Pol Calib' tab:
DST Port4 LP 'in', Ctr 0, Start 0, Step 0, Cpos 0
DST Port4 WP 'in', Ctr 180, Start 0, Step 10.0, Cpos 0
Set Loop to 36

push 'Burst'

Flatfields

Disk center, AO mirror un-flat, random guider
Same exposure time and co-add as the data

Darks

Put Port 4 dark in
Same exposure time and co-add as the data and flat fields

Grids and Targets

Disk center, AO mirror un-flat
Take a grid and target scan as you would a data scan, at least once per run.

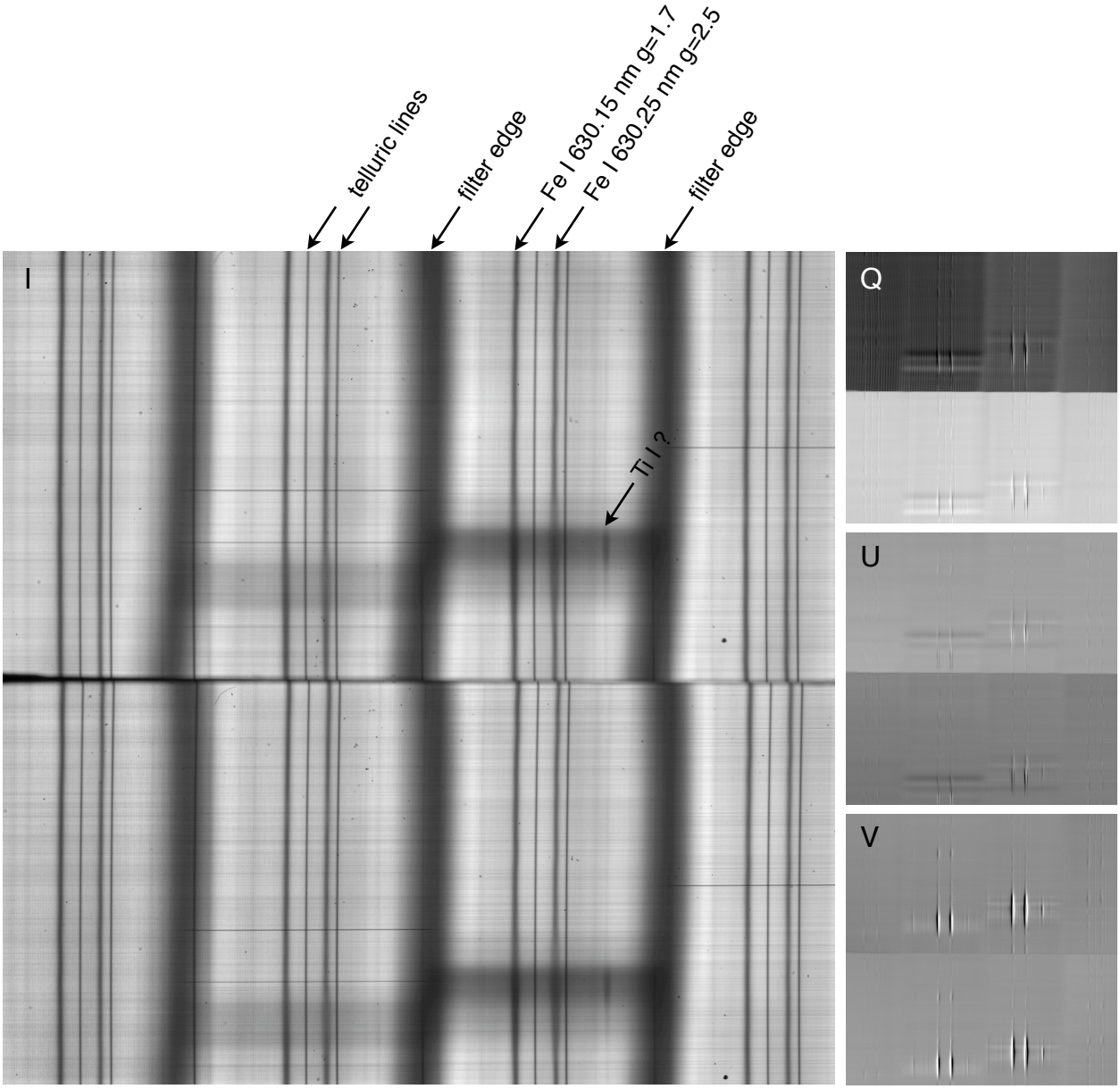
Suggested Observing Cadence:

scan, scan, flat, dark, pol cal
swap wavelengths (if desired)
scan, scan, flat, dark, pol cal

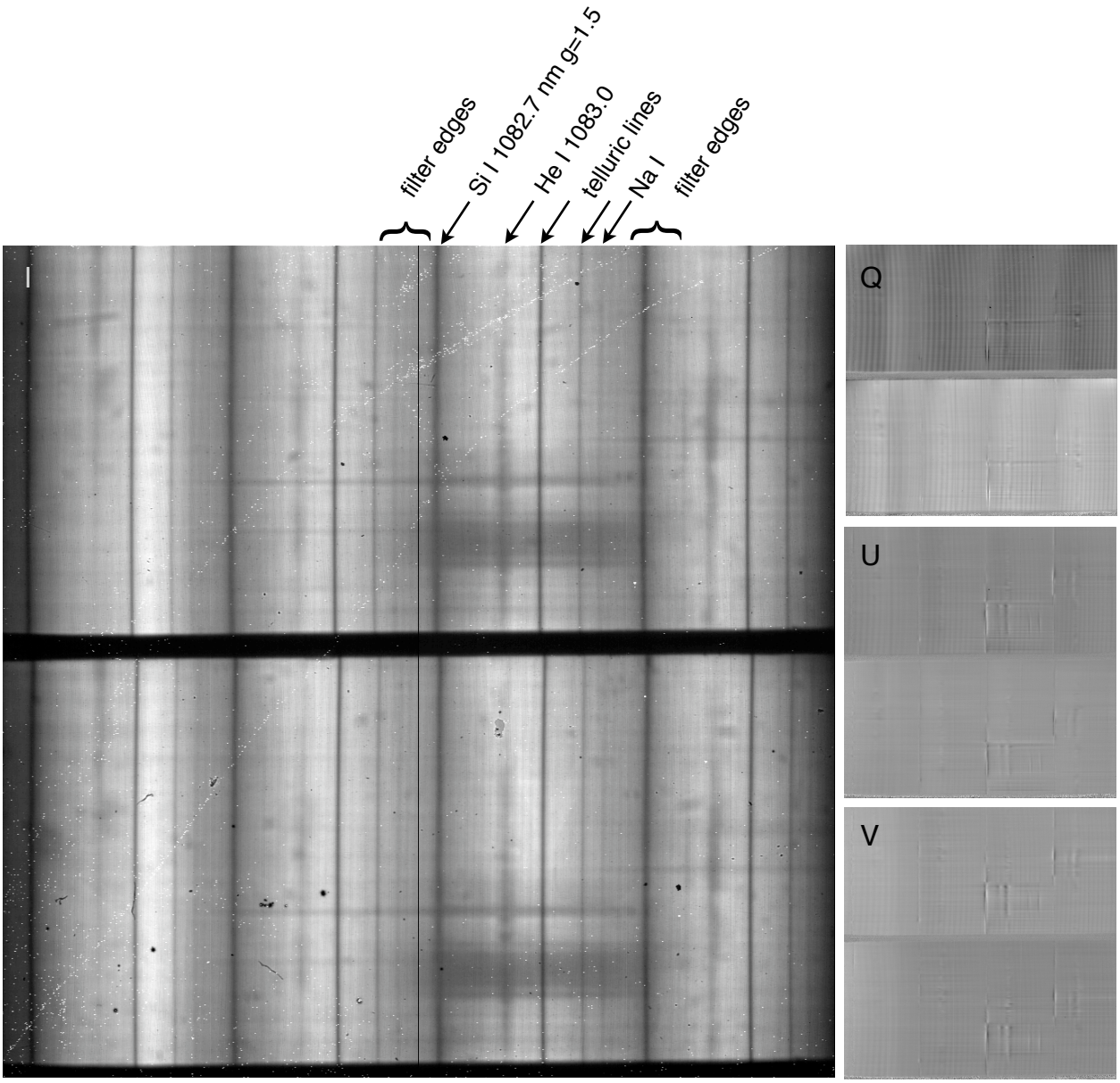
7. Examples of Data

On the next few pages we've included some samples of raw data with labels.

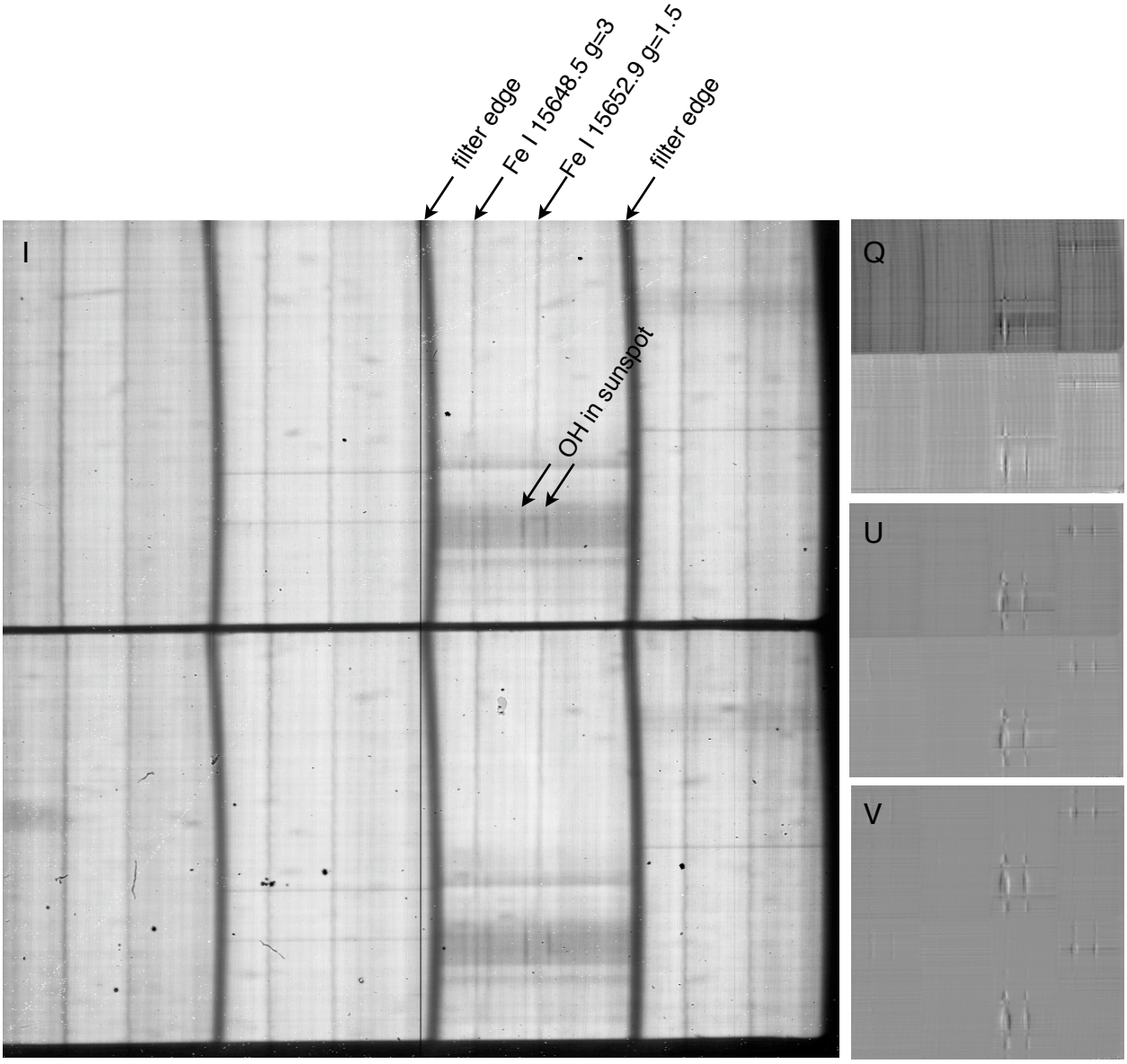
Fe I 630.2 nm:


telluric lines
filter edge
Fe I 630.15 nm g=1.7
Fe I 630.25 nm g=2.5
filter edge
Ti I ?
I
Q
U
V

He I 1083 nm:


filter edges
Si I 1082.7 nm g=1.5
He I 1083.0
telluric lines
Na I
filter edges
I
Q
U
V

Fe I 1565 nm:


filter edge
Fe I 15648.5 g=3
Fe I 15652.9 g=1.5
filter edge
I
OH in sunspot
Q
U
V